

1 **Market Potential of Nanoremediation in Europe –**
2 **Market Drivers and Interventions Identified in a Deliberative Scenario**
3 **Approach**

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6 **Abstract**

7 A deliberate expert-based scenario approach is applied to better understand the likely determinants
8 of the evolution of the market for nanoparticles use in remediation in Europe until 2025. An initial set
9 of factors had been obtained from a literature review and was complemented by a workshop and
10 key-informant interviews. In further expert engaging formats – focus groups, workshops,
11 conferences, surveys – this initial set of factors was condensed and engaged experts scored the
12 factors regarding their importance for being likely to influence the market development. An
13 interaction matrix was obtained identifying the factors being most active in shaping the market
14 development in Europe by 2025, namely “Science-Policy-Interface” and “Validated information on
15 nanoparticle application potential”. Based on these, potential future states were determined and
16 development of factors discussed. Conclusions are offered on achievable interventions to enhance
17 nanoremediation deployment.

18 **1 Introduction**

19 Globally, technologies have been developed to remediate contamination in soils and groundwater.
20 However, the cost and challenge associated with the treatment of groundwater in site-specific soil-
21 sediment-water systems on the one hand and the increasing awareness or emergence of so far
22 unknown contaminants call for a continued improvement and innovation in remediation
23 technologies. Such innovations – in particular when compared to established state-of-the-art
24 practices – offer opportunities but also can pose threads that determine the actual market
25 penetration potential.

26 Nano-particles (NPs) based/enhanced remediation approaches, so-called nanoremediation, are a
27 recent example of such an innovative technology. Different NPs – with a dimensions of less than
28 100nm (cf. Rauscher et al. 2014) – have been tested and developed to support reduction, oxidation,
29 sorption or a combination of these processes as *in situ* treatment of contaminated groundwater and
30 soil. The first documented field trial of nZVI, in 2000, involved treatment of trichloroethylene in
31 groundwater at a manufacturing site in Trenton, New Jersey, USA (Elliott & Zhang 2001). Several
32 commentators anticipated that nZVI technology would take off rapidly because of its perceived
33 benefits, such as rapid and apparent complete contaminant degradation. In 2007, a European report
34 forecasted that the 2010 world market for environmental nanotechnologies would be around six

35 billion US-Dollars (Rickerby & Morrison 2007). However, the uptake of the technology has been
36 relatively slow compared to other contemporary process based technologies.

37 Bardos *et al.* (2011) identified just 58 projects documented worldwide at pilot or full scale. The use of
38 nZVI in remediation practice was largely a niche application for chlorinated solvents in aquifers,
39 competing with more established techniques such as *in situ* bioremediation, chemical reduction and
40 granular ZVI (e.g. in permeable reactive barriers). The limited adoption of nZVI was linked to cost
41 uncertainty of the technology considering the unclear balance of benefits versus risks of NP use in
42 remediation and a lack of well documented / validated field scale deployments. Whereas advocates
43 emphasize the promising possibilities offered by the unique characteristics of NPs for extending the
44 range of available *in situ* remediation technologies, offering particular benefits in certain applications
45 (O'Carroll *et al.* 2013, Bardos *et al.* 2011), critiques raise concerns related to cost uncertainty and due
46 to insecurity related to behaviour, fate and toxicity of NPs: Some disputants point out unforeseen
47 contamination, potentially caused by the release of NPs to the environment – a notable dread that
48 might cause reluctance also amongst regulators (Bardos *et al.* 2016).

49 Various external determinants from economy, technology development, politics and society affect
50 the industry for contaminated land remediation (cf. van Liedekerke *et al.* 2014). The risks and
51 benefits of nanotechnology in general (e.g. Groves 2013; Robinson 2009; Ronteltap *et al.* 2011; Selin
52 2007; Wiek *et al.* 2013) and NP supported options augmenting the remediation market have been of
53 increasing interest (Karn *et al.* 2009, Bhawana & Fulekar 2012, Bardos *et al.* 2014). Yet, it is highly
54 uncertain what the drivers of this market are and how they develop in the future.

55 In order to understand the nanoremediation market characteristics and the uncertainties central to
56 its development, the opportunities for exploitation and routes for better regulation have to be
57 identified. Existing scenario studies on nanotechnology have been criticised for being “studies more
58 inspired by fiction than by science” (Wiek *et al.* 2009: 285). Therefore, we applied a “scenario”
59 approach that provides insights into the diversity of factors that potentially influence the future
60 development of the nanoremediation in Europe - including its institutional setting. Dialogue with
61 stakeholders has been crucial in the applied scenario development process. Their cross-sectorial and
62 transdisciplinary expertise was gathered to identify and evaluate determinants of the development
63 of the nanoremediation market – an approach that can be applied also in other innovative
64 technology assessments. It is based on a (grey) literature review and (expert) stakeholder
65 involvement via interviews, questionnaires, focus groups and workshops to conclude on
66 interventions in the market development. The overall approach is discussed in more detail in Bardos
67 *et al.* (2015).

68 This contribution identifies key factors that foster or inhibit the evolution of the nanoremediation
69 market in Europe by 2025 based on the application of an exploratory, deliberative scenario approach.
70 Our goal is to identify achievable interventions to enhance nanoremediation deployment offering
71 insights for “real-world” business development, deducing strategies for market activities, informing
72 policy development and/or regulatory authorities and add a case study to the scenario literature.
73 Section 2 provides a general background on the scenario methodology and data used in our
74 approach. Section 3 presents the results of the expert involvement activities and how these led into
75 the identification of key market development determinants. Section 4 offers a conclusion on key
76 lessons and suggests specific achievable interventions based on the identified scenario development.

77 **2 Methodology and data**

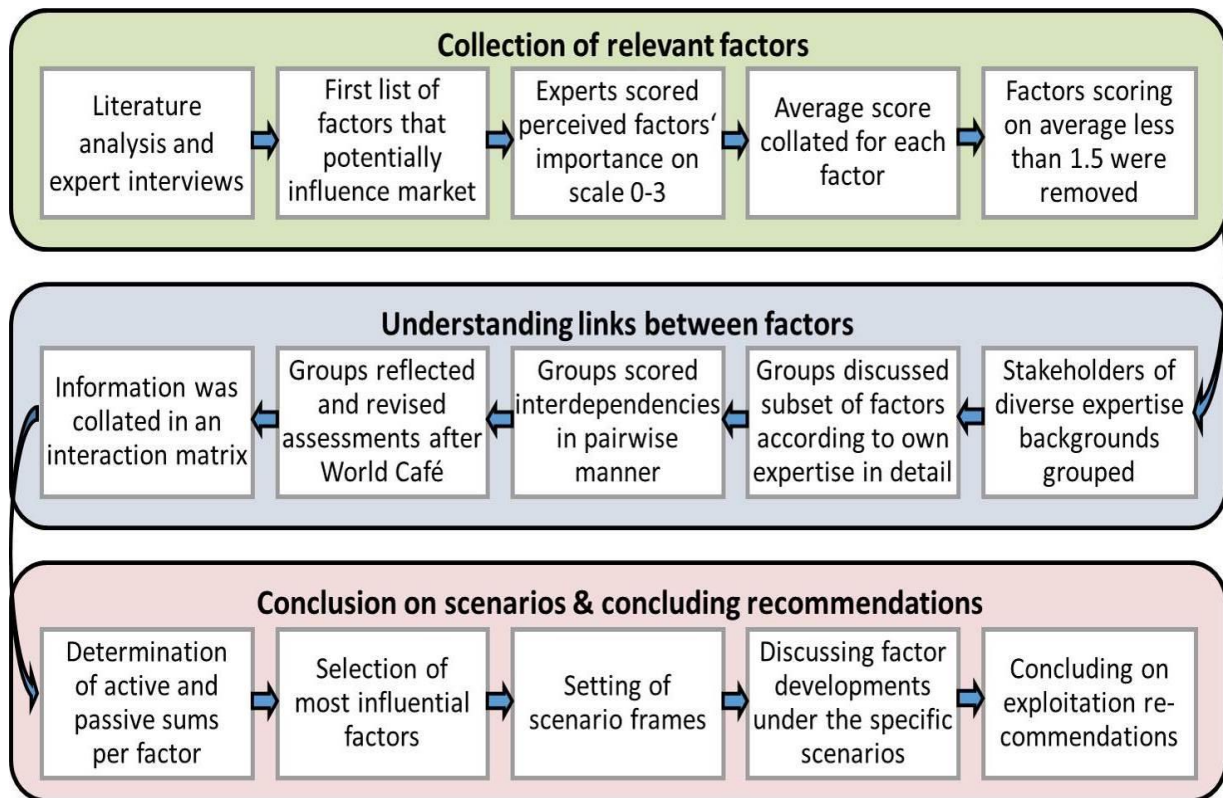
78 Scenarios can be defined as “internally consistent stories about ways that a specific system might
79 evolve in the future” (March et al. 2012: 127). Scenarios are applied to uncover and examine the
80 pertinent complexity of a system – in this case the nanoremediation market. Scenario analysis builds
81 on both i) a system thinking approach, which means it is acknowledging that actors are part of a
82 complex network of manipulable and uncontrollable drivers, which are connected to each other; and
83 ii) the ability to think in multiple futures, i.e. actors do not reduce strategic thinking to merely one
84 precise anticipated future, instead, they insure alternative futures are generated and applied in
85 strategic management (Gausemeier et al. 1998). Scenarios help to understand i) what drivers are, ii)
86 what the extent of their impact is, iii) how they are interlinked. These insights allow systematising
87 these drivers and the uncontrollable and persistent uncertainties related to them. For example,
88 regulation might be a decisive driver in the case of nanoremediation, yet only if policy making is
89 uncertain, it becomes an ambiguous element.

90 Deducted scenario storylines support identification of alternative development trajectories (Priess &
91 Hauck 2014) and can serve as a basis for concluding planning-oriented, responsive or proactive
92 strategies for enterprises (Gausemeier et al. 1998, Güemes-Castorena et al. 2013). Moreover, they
93 allow for detecting routes by which the development of the future can be governed by policy makers
94 (Priess & Hauck 2014, Volkery & Ribeiro 2009). Our goal is to identify achievable interventions to
95 enhance nanoremediation deployment.

96 Scenario design and analysis differ (see for example van Notten et al. 2003 or Alcamo 2009), but
97 usually comprise a stepwise approach including: i) a present situation analysis via ii) systemising, i.e.
98 understanding and filtering, the key factors and iii) their potential progression into the future to iv)
99 elaborating internally consistent stories about ways that the system might evolve in the future to v)
100 deducing strategies and governance guidance. Scenarios can be established through participatory or

101 through individual, often analytically based research approaches (van Notten et al., 2003; Alcamo
102 2009). A participatory approach captures the high diversity of drivers affecting the system and
103 identifies potential adaptations (March et al. 2012). The advantage of the participatory approach is
104 to support a realistic identification and feedback on the assessment of socio-economic drivers and
105 the recommendations deduced from the discussion of drivers to be relevant for the stakeholders.
106 Involving in particular experts ensures the relevance of the work for practical stakeholder needs,
107 decision support as well as for recommendations on exploitation strategies.

108 Given the novelty and complexity of the nanoremediation market case, we selected a methodology
109 that considers the challenge of significant (perceived) uncertainties regarding NP use as such and a
110 foresight investigation utilising the advantages of participatory scenario techniques. Guidelines in
111 Rizzo et al. (2015) were considered for i) identifying stakeholders; ii) differentiating between and
112 categorising stakeholders; and iii) investigating relationships between stakeholders as a preliminary
113 step. Different expert engagement formats were utilised. Based on the differentiation by Enengel et
114 al. (2012) between i) information, ii) consultation, iii) knowledge co-production and empowerment,
115 the selected degree of engagement is mostly the “consultation” level, consisting of gathering
116 information from participants (Alexandrescu et al. 2017, Rowe & Frewer 2000). Three methods were
117 adopted in order to leverage a wide knowledge flow from experts that bring in a wide range of
118 competencies: i) personal key-informant interviews (Gilchrist & Williams 1999), ii) structured
119 questionnaires and iii) meetings in the form of workshops, conference special sessions and focus
120 groups. In fact, it is a common practice to use a combination of methods (NOAA Coastal Services
121 Center 2009), in particular combining meetings with questionnaires (Morgan 1996, Rizzo et al. 2015).
122 Interviews and questionnaires were used to collect information and identify potential factors,
123 whereas workshops and focus groups were of key importance to understand the interrelation of
124 drivers. The applied method is summarised in Figure 1.



125

126 **Fig. 1:** Scenario development process in NanoRem project

127

128 First, following the general step-wise approach of scenario development, the current situation of the
 129 research object – the nanoremediation market – had to be outlined to ground the definition and
 130 interpretation of scenarios. This inquiry is usually based on a *literature analysis*. We mainly built up
 131 on previous work by Bardos et al. (2014) – and augmented this in a participatory approach with
 132 information collection from conducting *an expert meeting and semi-structured key informant*
 133 *interviews* (Gilchrist & Williams 1999). Although the accessible literature permits for deductions
 134 about general conditions and drivers for NPs production and application in remediation projects, the
 135 main purpose of these interviews with at least three experts representing different backgrounds
 136 (scientist, NP producer, regulator) was 1) to deliver a practitioners' check and extension of the
 137 literature results, and 2) to identify specific stakeholder/ market needs and interests regarding
 138 nanoremediation. The result of the step was the collection of a *first list of factors that potentially*
 139 *influence the nanoremediation market system*.

140 The second step was to systematise the initial set of drivers by revealing the importance of and
 141 linkages between identified factors. Questionnaires were designed and distributed 1) project
 142 internally and 2) at several topic-related events with the aim to include experts' knowledge in the
 143 (broader) field of nanoremediation. The survey asked to 1) add "missing" drivers and 2) to indicate
 144 the kind of dependency between drivers.

145 Third, to understanding the links between factors, information on factor relations was collated in an
 146 *interaction matrix* (cf. Gausemeier et al. 1998), which comprises the assessment of the strength with
 147 which each variable affects the other variables and is in turn affected. Visualising the results of this
 148 assessment in such a system grid, each factors' relative role and degree of integration in the system
 149 can be discussed and evaluated. In a workshop, experts were brought together. They were
 150 introduced to the objective of the study and were asked to 1) review the linkages of drivers, 2) select
 151 those drivers that significantly influence the system's development, and 3) disclose potential future
 152 developments of these variables. According to Wiek et al. (2009) future projections can be based on
 153 extrapolation from present trends, prognoses, transfer of circumstances from similar systems, and
 154 existing scenarios. However, most important in our approach were the expert opinions as collected
 155 in the workshops. Extreme and opposed projections were particularly interesting, because these
 156 highlight drivers and inhibitors most clearly.

157 Forth, based on these results, several focus groups of experts with different backgrounds reviewed
 158 the interim results and discussed the potential developments of factors into potential future states.
 159 At these occasions, the aim was to compile the projections of the key drivers into four scenarios
 160 based on identification of two critical uncertainties (cf. Kelly et al. 2007; Tietje 2005). These scenarios
 161 formed simple narrative descriptions of the potential future market situations and the developments
 162 leading from the present to these alternate futures (Gausemeier et al. 1998). As Rizzo and colleagues
 163 (2015) describe, focus groups are a special type of stakeholder engagement used to collect
 164 information from a limited number of members of a clearly defined target audience. Participants are
 165 guided by a facilitator through a discussion focussing on several related topics in order to collate
 166 opinions and expertise of group members in a comfortable environment (Rennekamp & Nall 2003).
 167 Such settings enable participants to define and frame their individual points of view by comparing
 168 them to others' perspectives (Rizzo et al. 2015).

169 The fifth step of the analysis consists of interpreting the future scenario states and collating
 170 feedbacks from experts to derive recommendations for interventions for nanoremediation
 171 exploitation. Interim results were presented at the AquaConSoil conference in 2017 for review.

172 Table 1 summarizes the expert engagement means and provides an overview of the database for the
 173 results reported in the following section.

174 **Table 1:** Overview of input sources for the scenario development and assessment indicating times, scenario development
 175 stages as well as characteristics and methods of input.

What	When	Characteristics / methods of input
Present situation analysis – identification of preliminary list of market influencing factors	06-10/2014	<ul style="list-style-type: none"> • (Grey) Literature review based on Bardos et al. (2014) • Project meeting (9 pers), Reading, UK, 14/07/2014 • Semi-structured interviews with 3 key informants (1 scientist, 1 regulator, 1 public perception/risk expert)

		<ul style="list-style-type: none"> • Questionnaires distributed project internally and at conferences CSME-2014/SARCLE-2014, San Diego, USA, 02-04/09/2014, and CABERNET-2014, Frankfurt, DE
Systematising factors: identification of links (interaction matrix), conclude on scenario framing factors	11/2014-07/2015	<ul style="list-style-type: none"> • Workshop (36 pers), Oslo, NO, 02-04/12/2014 • Online survey
Review of dependencies and discussion of different plausible developments of the significant factors	02/2015-09/2016	<ul style="list-style-type: none"> • Focus group (14 pers), Berlin, DE, 11/03/2015 • Special Session at AquaConSoil 2015 (ca. 10 experts), Copenhagen, DK, 11/06/2015 • Focus group (23 pers), London, UK, 13/07/2016 • Special Session at RemTech 2016 (8 pers) Ferrara, IT, 21/09/2016
Discussion of broader factors development and deriving recommendations for interventions	11/2016-07/2017	Discussion of interim results and gaining review / feedback of conclusions in online consultation / questionnaire and with experts at AquaConSoil 2017 Lyon, FR, 27/06/2017

176 3 Results

177 3.1 Establishing the Baseline for Scenario Development

178 In order to conclude on a first set of factors that potentially determine the nanoremediation market
179 evolution, a literature review was conducted by Bardos et al. (2014) providing a risk-benefit appraisal
180 of nZVI for remediation. To further understand the status quo of the nanoremediation technology
181 and reveal market prospects, this review was complemented by a workshop with experts having
182 backgrounds in science, industry and economics. This preliminary research helped establishing a
183 variety of external determinants from economy, technology development, politics and society.

184 A first list of about thirty factors was further substantiated in key-informant interviews with three
185 experts (a European level policy maker in contaminated land regulation, a scientist working on NP
186 development for remediation and a researcher working on societal perception and health risks of
187 MPs in general). The purpose of the interviews was i) to deliver a practitioners' check and extension
188 of the literature results, and ii) to identify specific stakeholder/ market needs and interests regarding
189 nanoremediation. The interviews were complemented by questionnaires.

190 The result of the step was the collection of a *first list of factors that potentially influence the*
191 *nanoremediation market*. Key informant interviews were also utilised to establish the most
192 worthwhile timeframe for the scenario approach. The consensus was that evolution of the market up
193 to 2025 was the most appropriate scope. It was felt that a long-term assessment would be
194 impossible due to the significance of unknown and uncertain potential developments. A shorter
195 outlook, would have been too close to allow for making adjustments in business or regulation based
196 on exploitation/intervention recommendations. After the literature and interview scoping phase, a
197 condensed list of 22 potential factors was established.

198 **3.2 Systematising Market Development Factors**

199 To aid step two of the scenario design, an expert workshop was held in December 2014 and a web-
200 consultation process was held.

201 The workshop involved 36 participants from nine different countries, including land managers,
202 consultants, technology contractors, planners, regulators and other experts, with various background
203 and interests. In order to further condense the list of factors determined in the preliminary research
204 stage, workshop participants were asked to provide an assessment in preparation of the workshop
205 on how important they perceived each factor to be for the development of the EU nanoremediation
206 market by 2025. Participants scored each factor’s relevance from 0 = negligible via 1 = minor, 2 =
207 considerable to 3 = key relevance to push or pull the nanoremediation market’s development. In
208 total 20 responses were collated and the arithmetic mean was calculated for each factor.

209 Table 2 presents the list of factors (column 1) in descending order of obtained scores (column 3). At
210 first glance the scores allow to conclude: 1) there is no “key factor” (average scoring >2.50) alone
211 pushing or pulling the nanoremediation market. 2) A wider set of considerably important factors
212 influences the market. 3) Factors indicating *Megatrends* and some related to *Economy* and *Society*
213 have only minor relevance. 4) Market development depends not only on technology, but also on
214 political (dis)incentives, societal preferences or the attitude of the industry. Several driving factors
215 are difficult to predict and to influence, such as public perception of NPs in general or environmental
216 protection policies. Interdependencies with other fields, such as finance and regional development,
217 technology and nature protection, are ample. Some of the scorings, e.g. the ability to treat emerging
218 contaminants with NPs, appear to be surprising and may indicate either bias or epistemic issues in
219 the mind of the responders.

220 **Table 2:** Factors, definitions, their perceived importance with regards to influencing nanoremediation market development in
221 the EU up to 2025 and categorization

Factor	Factor description	Score	Category
Most important factors (≥2.00):			
Innovation on treatment of known contaminants with NPs	NPs are effective in treating a range of contaminants. They may be superior to existing remediation approaches (being quicker or cheaper to apply or offering another added value) on a site specific basis.	2.48	Technology
Regulation of nanoparticles	While moratoria against use of NPs for remediation still exist in a few instances, the emerging trend is that NPs can be deployed using existing regulatory regimes. Uncertainties are those experienced in general for the injection of “new” types of material into the subsurface.	2.45	Policy / Regulation
Validated information on NP application potential	‘Information’ dimension describing the quality of available information for decision-making. Information quality can range from a level with great uncertainty with regards to the potential developments of the market and the set of factors driving the market, to a situation where information about nanoremediation is readily available, well tested, and broadly accepted (i.e. “validated”).	2.40	Communication

Costs of competing technologies	There are already competitive nanoremediation technology solutions, but their international market penetration is low and they face strong competition from more established in situ technologies. Cost effectiveness is highly site specific	2.35	Economy
Standardisation for nanoparticles	- excluded from further analysis - *	2.20	Policy / Regulation
Innovations along NP production chain	The production of NPs could be boosted by improved efficiency based on increasing knowledge and economies of scale, making NPs cheaper.	2.18	Technology
Environment (especially soil) protection policies	There is policy uncertainty at a European level for remediation drivers in general (e.g., withdrawal of Soil Framework Directive versus increasing concerns over 'emerging contaminants'). Specific to nanoremediation: 'moratoria' against use exist in some countries/regions, but these may be reconsidered, particularly as a result of current research work.	2.10	Policy / Regulation
Synergies with other technologies	NPs can be applied in remediation integrated with other approaches, e.g. bioremediation.	2.05	Technology
Public stakeholder dialogue	Refers to communication with general public. Risks, uncertainties and benefits should be communicated in targeted formats with relevant public stakeholders. (Dialogue work currently being conducted in the UK may indicate increasing acceptability of nanotechnology use in remediation.)	2.00	Communication
Less important factors (>1.50 and <2.00)			
NP treatment of emerging contaminants	NPs are may be effective in remediating various emerging contamination problems, but research and practical experience are fairly limited at present.	1.95	Technology
Public perception of NPs in general – What people think of “nano”	Public perception of NPs is patchy with low consumer knowledge and ambiguity in risk perception. The increasing use of 'nano-products' implies increasing levels of public acceptance for the technology in general, although concerns over some specific potential pollutants such as nano-silver remain.	1.93	Society
Science-Policy-Interface – Communication with others	Broadly understood as 'Dialogue' process by which stakeholder groups (in particular those from science, policy and regulation) have informal/formal discussions, consultations and other forms of engagement in order to ascertain the potential application of nanoremediation (in general or in specific cases).	1.93	Communication
Technology and research policies	European and national policies fund R&D into innovative technologies, generating new knowledge, including a range of nanoremediation R&D and demonstration work (such as NanoRem).	1.75	Policy
Growing number of nanoparticles suppliers	More producers are entering the market. Suppliers are typically remediation service providers, such as consultancies. More suppliers are considering nanoremediation, although the number investing in expertise, capacities and credibility to provide nanoremediation remains relatively small at present.	1.73	Economy
Real estate market development	The property market has begun to recover since the financial crash increasing the demand for suitable areas for development – which in turn influences the demand for the remediation of contaminated land.	1.68	Economy
Innovation attitude	There is an increasing openness in the remediation sector towards innovation paired with willingness to invest in inventions and knowledge creation along with greater readiness to apply innovative technologies.	1.60	Society
Environmental awareness	There is increasing support for ensuring a more sustainable approach to contaminated land management, and this will increasingly affect remediation decision-making. This is a highly site specific consideration.	1.55	Society
Minor relevant factors (≤1.50)			
EU economic development	- excluded from further analysis - **	1.50	Economy
Globalisation	- excluded from further analysis - **	1.20	Megatrend

Industrial and military land use	- excluded from further analysis - **	1.00	Society
Climate change	- excluded from further analysis - **	0.70	Megatrend
Demographic change	- excluded from further analysis - **	0.60	Megatrend

222 * Consulted regulation and policy making experts rejected this category as not meaningful (as NPs
223 are considered in existing regulation, such as REACH). Therefore it was omitted.

224 ** Consulted experts agreed to omit all factors with a score of < 1.5 from further assessment.

225

226 At the workshop itself, participants were introduced to the state-of-the-art of nanoremediation
227 technology, a sustainability assessment exercise and the general scenario approach. Based on
228 presentation of the factor list and average assessment scores (Table 2, column 3), experts agreed to
229 omitted all factors with a score of < 1.5 from further assessment. Also, no expert claimed that a
230 specific factor was missing, confirming completeness of a list of 17 important factors. To assess
231 interdependencies of these, participants were divided into equally large groups based on their field
232 of expertise matching with a categorisation of factors (Table 2, column 4): Factors related to/Experts
233 for *Technology, Communication, Economy, Society and Regulators & Policy makers*.

234 First, groups reviewed and revised the draft definition provided for each factor in their domain.
235 There was an overall intense discussion in all groups. First descriptions of factors were perceived as
236 not specific enough. All determinants were specified with the exception of “Standardisation” – this
237 factor was rejected and finally deleted from the list for reasons of ambiguity and regulators’
238 emphasis that NP fall under existing regulation and standards, such as REACH. The revised
239 descriptions obtained are presented in column 2 of Table 2.

240 Second, groups were asked to discuss and score the interrelations of the development of each of
241 their factors on the full list of factors – thereby establishing a part of the interaction matrix.
242 Considering the European Union in 2025, the impact of the development of each factor in a row
243 (expert groups factor) on the development of the factor in each column (complete list of factors) was
244 judged on a four-part scale from “No impact” to “Strong / direct impact”. Next, applying the World
245 Café format (Schieffer et al. 2004), expert groups reviewed one-by one the assessments of each of
246 the other groups, indicating consent or disagreement with the respective assessments. Finally,
247 assessments were revised considering the feedback process. At the end of the session, the annotated
248 posters and notes of facilitators were collected and interpreted.

249 After the workshop, the information and scores from the group sessions were collated into an
250 interaction matrix (Table 3). This allows identification of the factors that are more “active” in
251 influencing other factors (highest sum in a row), as well as those that are more driven by the active
252 ones (highest sum in the column).

Table 3: Interaction matrix identifying degree of influence of each factor (determining the development of the nanoremediation market in Europe by 2025) on each of all other factors

Interaction matrix <i>Scoring of influence of factors in a row on factor in a column:</i> 0 = No impact 1 = weak and delayed impact 2 = medium impact 3 = strong and direct impact	Innovation on treatment of known contaminants with NPs	Regulation of nanoparticles	Validated information on NP application potential	Costs of competing technologies	Standardisation for nanoparticles	Innovations along NP production chain	Environment (especially soil) protection policies	Synergies with other technologies	Public stakeholder dialogue	NP treatment of emerging contaminants	Public perception of NPs – What people think of “nano”	Science-Policy-Interface – Communication with others	Technology and research policies	Growing number of nanoparticles suppliers	Real estate market development	Innovation attitude	Environmental awareness	Active sum*
Innovation on treatment of known contaminants with NPs		0	0	3	2	2	0	2	1	1	1	0	2	3	1	3	1	22
Regulation of nanoparticles	3		3	0		0	3	0	2	3	1	3	3	2	0	0	0	23
Validated information on NP application potential	3	3		2	2	2	3	3	3	2	3	3	1	1	1	1	3	36
Costs of competing technologies	3	2	2		2	3	0	3	0	1	0	2	1	3	0	2	0	24
Standardisation for nanoparticles																		0
Innovations along NP production chain	2	0	0	3	3		0	2	0	3	0	0	2	3	1	3	2	24
Environment (especially soil) protection policies	3	3	3	0		0		0	3	3	1	3	3	2	0	0	1	25
Synergies with other technologies	3	0	0	3	2	2	0		1	2	1	0	2	3	1	3	1	24
Public stakeholder dialogue	1	3	3	1	1	0	3	0		0	3	3	2	1	1	0	3	25
NP treatment of emerging contaminants	0	0	0	2	1	2	0	1	0		2	0	3	3	1	3	1	19
Public perception of NPs – What people think of “nano”	0	1	0,5	0	0,5	0	1	0	3	0		2	1	2	0	2	1	14
Science-Policy-Interface – Communication with others	3	3	3	2	2	1	3	2	3	3	3		2	2	1	2	3	38
Technology and research policies	3	0	2	1		2	2	1	1	3	1	3		1	0	2	1	23
Growing number of nanoparticles suppliers	2	2	2	3	2	3	0	2	1	2	1	1	1		0	1	1	24
Real estate market development	1	0	1	3	1	0	0	1	2	0	0	1	0,5	1,5		0	1	11,5
Innovation attitude	1,5	0	0	1	0	2	0	2	0	2	2	2	2	2	0		0	16,5
Environmental awareness	1	2	1,5	0	0,5	2	2	1	1,5	1	2	3	2	0	1	2		21
Passive sum*	29,5	19	21	24	19	21	17	20	20	26	21	26	27,5	28	8	24	19	

255 *Active and passive sums had a maximum potential value of 48 (i.e. a scoring of 3 for each pair-wise assessment with the 16
 256 other factors). The closer the active sum for a factor is to 48, the more influential that factor is. Conversely if the passive sum
 257 for a factor is close to 48, it is likely to be highly influenced by changes in other factors. Assessments are based on workshop
 258 with 36 experts from diverse backgrounds in Dec. 2014.

259

260 The key conclusion from the interaction matrix (Table 3) is, that the factors “Science-Policy-Interface”
 261 and “Validated information on NP application potential” are by far the two most active drivers and,
 262 hence, most crucial in determining the development of all factors which influence the evolution of
 263 the nanoremediation market. Looking at the passive sums, the factors are less pronounced
 264 distinguishable. The three factors most heavily being influenced in their development by the other

265 determinants are “Innovations in treatment of known contaminants with NP”, “Growing number of
266 nanoparticles suppliers” and “Technology and research policies”.

267 To add the range of engaged experts, the knowledge base was complemented by an online
268 consultation, which was made available between April – July 2015 (see Bardos et al. 2016). Experts
269 were invited to specify a list of factors, which were clustered from the full list of factors in Table 3.

270 In general, the feedback of the online consultation is found to be in line with the discussions at the
271 expert engagement events. Experts expect improvements of nanoremediation competitiveness as
272 costs are likely to remain the same or improve against other competing technologies. The majority of
273 experts also identified that by 2025 relative effectiveness of nanoremediation would stay the same
274 or improve.

275 **3.3 Projection of Factor Development and Establishing Consistent Scenarios**

276 A series of focus group style events between March 2015 and September 2016 engaged in total 55
277 experts (cf. Table 1) from across Europe. Basically, all events were to follow the same agenda: first,
278 participants were introduced to the state-of-the-art regarding the NP remediation technology and,
279 second, to the scenario approach. The technology had a focus on nZVI as most commonly
280 documented NP so far in remediation. Yet, it also accounts both for new information and a slightly
281 wider range of NPs was included. Third, the development of market factors was discussed. The
282 events were held in different countries (in particular Germany, UK, Italy) across Europe to collate
283 expert knowledge in the different settings.

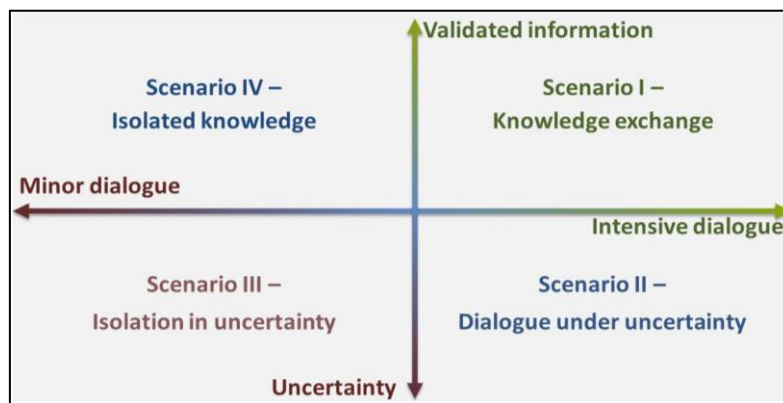
284 In the first event, experts were shown that the two most “active” of the key factors were identified
285 as: “Science-Policy-Interface” and “Validated information on NP application potential” (see Table 3).
286 Experts agreed that these factors are likely most crucial in determining the development of the
287 nanoremediation market. These two factors were suggested to develop framing elements for a
288 conceptual scheme of scenario future states, which are understood as possible futures. The
289 participants discussed the meaning of these factors and defined them as follows:

- 290 • **Science-Policy-Interface** is part of a broader ‘**Dialogue**’, which is the process by which
291 stakeholder groups (in particular those from science, policy and regulation) have
292 informal/formal discussions, consultations and other forms of engagement in order to ascertain
293 the potential application of nanoremediation (in general or in specific cases).
- 294 • **Validated information on NP application potential** is an ‘**Information**’ dimension,
295 which describes the quality of available information for decision-making. Information can range
296 from a level of great uncertainty with regards to the potential developments of the market and
297 the set of factors driving the market, to a situation where information about nanoremediation is

298 readily available, well tested, and broadly accepted (i.e. “validated”). “Validated
299 information” gives credence to a decision regarding its applicability.

300 In all following expert events, this selection of framing factors and their definitions were confirmed.
301 These factors form the conceptual frames for the scenario states describing four possible futures of
302 the nanoremediation market in Europe in 2025 (Figure 2, clock-wise in each quadrant of the matrix):

- 303 • Scenario I “Knowledge exchange”: Validated information is broadly available AND there is
304 comprehensive dialogue between stakeholders, in particular those from science, policy and
305 regulation.
- 306 • Scenario II “Dialogue under uncertainty”: Validated information is lacking and uncertainty is still
307 significant BUT there is comprehensive dialogue between stakeholders, in particular those from
308 science, policy and regulation.
- 309 • Scenario III “Isolation in uncertainty”: Validated information is lacking and uncertainty is still
310 significant AND there is no or only minimum dialogue between stakeholders, in particular those
311 from science, policy and regulation.
- 312 • Scenario IV “Isolated knowledge”: Validated information is broadly available BUT there is no or
313 only minimum dialogue between stakeholders, in particular those from science, policy and
314 regulation.



315

316 **Fig. 2:** Scenario states describing four possible futures of the nanoremediation market in Europe in 2025

317

318 This framework has been the basis to discuss in various formats in the workshops the plausible
319 developments of factors. The aim was to identify in these discussions the disruptive events and
320 decision points in order to deduce recommendations for the exploitation of nanoremediation.

321 The German focus group in March 2015 was a meeting of practitioners, regulators and academics
322 dealing with NPs and/or remediation. The meeting confirmed the importance of the key factors
323 “availability of valid information” and “dialogue between stakeholders” as meaningful framing

324 variables of plausible future states of the market. The group strived for a joint understanding a
325 concretisation of these two factors which were hence used and confirmed in the following
326 engagement activities. Moreover, the groups draw some key conclusions on the potential market
327 development for nanoremediation. Consultant, market and industry representatives emphasised the
328 need for more documented applications and success stories of the technology's application. The role
329 of trustworthy communicators and knowledge arenas (such as AquaConSoil, DECHEMA or Battelle)
330 was highlighted. The necessary recognition of the site specificity was pointed out in this respect, too.
331 Research funding could support closing the knowledge gap, in particular related to risk
332 understanding with public research and for elucidating the innovative potential with research driven
333 by market interested industry and consultants. Overall, a concentrated dialogue of problem owners,
334 consultants, researchers and regulators was stressed to be essential.

335 The UK focus group in July 2016 also confirmed the key market determinants being available
336 validated information and dialogue of stakeholders. Existing knowledge gaps need to be addressed. It
337 has been emphasised that nanoremediation is a site specific technology, so there is need to
338 demonstrate in the UK with its specific conditions its applicability to understand the performance
339 envelope of the technology. A specific need has been stated to clearly understand the human health
340 risks. Also a better understanding and documentation of the fate and transport of NPs is vital for
341 market development. In the specific context of the UK, the voluntary moratorium on environmental
342 release of NPs was a main topic of the focus group. It is understood to be a significant market
343 determinant in the country. Some UK workshop participants expressed hope that Defra will review
344 this in the light of emerging validated information availability. However, it was emphasised that the
345 moratorium does not prevent the regulator agreeing to pilot deployments of nanoremediation in the
346 field, which would support the creation of further validated information and exchange of actors, and
347 could ultimately support a case for the moratorium's removal. Last not least as summary,
348 opportunities are seen in the UK for nanoremediation.

349 The expert engagement at AquaConSoil 2015 and Remtech 2016 conferences confirmed the results.

350 **3.4 General Findings on Market Drivers**

351 A number of issues were identified in the interviews, workshops and survey. These related to
352 strengths of nanoremediation related to its *relative effectiveness* due to rapid contaminant
353 treatment where nano-activity is taking place as well as promising laboratory investigations
354 indicating for many contaminants that there is a complete destruction effect for chlorinated solvents
355 and, moreover, a wider treatable range of contaminants. Additionally, it was stated that NP
356 deployments tend to facilitate in situ dehalorespiration (a specific form of bioremediation).
357 Nanoremediation offers clear opportunities in its abilities to treat contaminants in the vadose zone,

358 potential for treatment of source terms, that integrated approaches (e.g. combining nano and micro
359 scale ZVI) may improve effectiveness and reduce costs (also opportunities with electro-remediation
360 and bioremediation approaches) and inclusion of nanoremediation in *in situ* integrated treatment
361 approaches.

362 Although most experts appreciated the increasing documented knowledge about nanoremediation,
363 there was at large concern that public domain publications of field scale deployments remain
364 relatively scarce and that examples are lacking of field deployments with comprehensive
365 sustainability assessment. Also, field scale deployments remain rather limited in the number of
366 contaminant types targeted. Similarly, public domain and validated reports of commercial
367 deployments are lacking. Limited availability of know-how for field based NP monitoring techniques
368 causes relative risks related to NPs next to handling risks. It was also stated that numerous coatings,
369 modifiers, catalysts could make establishing risks complicated. On the other hand, experts pointed to
370 studies indicating that ecotoxicological impacts of NPs would be limited in scale and duration. The
371 limited longevity of NP activity may reduce environmental risks and allow more targeted
372 applications. Yet, the limited migration in the subsurface may also require additional injection points.
373 Also, deployment retains a need for fairly specialised experience and know-how. The development of
374 more convenient deployment systems and information extending the range of potential service
375 providers able to deploy nanoremediation is considered being a challenge and opportunity.

376 An improved understanding based on more available knowledge could lead to reduced public and
377 regulatory fears. However, potentially significant public concern about nanotechnology being
378 inherently risky might remain as a threat to the market development.

379 As a summary, the existence of validated data on case studies is critical for market development – in
380 particular if this information can be told as success stories. In addition, dialogue between the
381 stakeholders (science – industry – policy – general public) is crucial. An open debate is the question:
382 Who is best to initiate the communication: Is scientific knowledge transferred to consultants and
383 then to regulators? – No answer was provided, but it became clear that those interested in the
384 promotion should invest, i.e. politics should support research in innovative NP to tackle emerging
385 contaminants and prevent risks to society; researchers should communicate their results in a way
386 that is understood by the market and regulators; consultants should invest in nanotechnologies to
387 gain from early mover advantages; and so forth. Regarding the key drivers identified in the scenario
388 process, the consultation results indicate the following: Related to “dialogue”, experts stated that
389 there was a low level of dialogue between most, including the scientific community, industry, and
390 regulators. Experts provided suggestions on how to improve the dialogue by “Independent scientists
391 – consultant who has no conflict of interest should be approached for an opinion – in order to have a

392 better understanding of all pros and against” and “there is nothing comparable to true success
393 stories written in an understandable manner”.

394 These success stories also link to the availability of “information”. Indeed, field scale experience was
395 identified as an important or very important by all experts. Related to this, the majority of experts
396 identified that the risk perception and technology dread were important factors related to available
397 information. Both are assumed to being likely to rather improve over the next ten years, stating “at
398 the moment, there is more risks assumed and feared than really shown to exist. This will change with
399 better knowledge basis.” All experts identified that current knowledge improvements was important
400 or very important if nanotechnology was to improve its use in the next ten years. The majority
401 expects that knowledge will improve in the next ten years.

402 The majority of involved experts expect that knowledge will improve in the next ten years by some
403 explaining their reasoning with “more complex information will be available” and “once seen as tried
404 and tested, practitioners will be more likely to apply it”. If it will be documented in a plausible way
405 and involved actors will speak about the outcomes, it will be far more likely to foster
406 nanoremediation and exploit the market for it. The experts provided suggestions how to improve
407 dialogue, e.g. by “Independent scientists - consultant who have no conflict of interest should be
408 approached for an opinion - in order to have a better understanding of all pros and against” and
409 “there is nothing comparable to true success stories written in an understandable manner”.

410 **4 Conclusions for Interventions**

411 The scenario assessment approach yielded a wealth of insights into the diversity of factors
412 influencing the potential market emergence of nanoremediation. In the focus groups and workshops,
413 several trends were identified as affecting the nanoremediation market. Table 4 suggests a series of
414 measures, that are readily achievable that could impact these trends to benefit strengths and
415 opportunities for nanoremediation, whilst mitigating for weaknesses and threats. These suggestions
416 are based on the focus group and expert discussions, as well as taking into account the existing
417 pattern of deployment summarised in the literature (e.g. Bardos et al. 2015). The analysis provides
418 an initial, and tentative, view on how time sensitive these may be and state, if they will change over
419 time; what the authors can say now about likely changes; and how certain these are.

420 **Table 4:** Readily achievable interventions to enhance nanoremediation deployment

Item	Possible trends to 2025	Certainty of development	Interventions
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Item	Possible trends to 2025	Certainty of development	Interventions
Relative costs	Economies of scale lead to cost reductions related to: a) production of NPs b) application of NPs Combined / integrated approaches bring costs down to competing options such as <i>in situ</i> bioremediation	Highly likely, scaled up production (early adoption) already occurring - and field deployments of engineered combined approaches already taking place.	Transfer of more readily usable nanoremediation systems to commercial scale manufacture of NPs and productising deployment applications and guidance. Effectively validated field scale deployments of combined / integrated approaches with release of reliable cost and performance data.
Field scale experience	Additional field trials including a wider range of contaminants could strengthen the evidence base for nanoremediation effectiveness and reduce public concerns associated with deployment safety	Highly likely. This has been a objective of recent research projects.	Replication of nanoremediation application via early adopters who might gain market edge in know-how / service delivery is facilitated by NanoRem outputs and guidance.
Relative effectiveness	a) Research funding to address difficult contaminants and develop novel NPs b) Vadose zone treatment could solve difficult / untreatable problems, such as highly recalcitrant contaminant classes c) Development of coatings to improve persistence and mobility	a) Highly likely – There are a number of research projects taking place across Europe b) Likely - Currently vadose zone treatment has not been well investigated, but exploiting NPs for this use may be possible c) Highly likely - Relatively certain, research being carried out	A range of related research projects are underway or at the proposal stage and the number of publications grows right across the academic community.
Relative risks	Additional risk due to development of coatings to improve persistence and mobility	Highly likely	A range of related research projects are underway or at the proposal stage.
Ease of use	Improvement and productising of nanoremediation deployment	Highly likely, research being carried out	Include productising as a key feature of field scale deployment projects.
Technology dread / scepticism	Gradually diminishing as an issue as research outcomes and information become more widely available.	More likely than not, however, unforeseen events are to be considered that might increase the dread, e.g. news about inefficient use and even contaminations (e.g. – and nonetheless if – caused by inappropriate use).	Improvement of overall information availability – in different formats for easy dialogue between different stakeholder groups – and simple information relating to appropriate use.
Current knowledge	Knowledge expansion leading, improved certainty of effectiveness, increased uptake of the technology, and more straightforward deployment and permitting.	Likely, scientific research projects as a major contribution towards this development, however, a mayor challenge is awareness amongst decision makers.	Improvement of overall information availability from multiple platforms to achieve a scenario where there is extensive exchange of well validated information.

421

422 The paper presented the individual steps and results of a deliberate scenario process to gain
423 information on key factors that foster or inhibit the evolution of the nanoremediation market in

424 Europe by 2025 based on the application. A key motivation was ensuring that research addresses real
425 market and regulatory interests. The analysis highlighted that the existence of validated data on case
426 studies is critical for market development – in particular if this information can be told as success
427 stories. Furthermore, stakeholder dialogue is crucial.

428 Any new technology has to prove that it is complementing or improving existing technologies at an
429 appropriate economic cost and acceptable risks. There are no absolute blocks to an uptake of
430 nanoremediation in the markets, but documented, validated case studies and understanding the
431 “operational window” of nanoremediation are found to be extremely significant. Research is seen by
432 experts as a disruptive element as results can help to deliver the required validated information –
433 however, academics must communicate these in an appropriate way to business and regulation.

434 Overall, the scenario process has significantly increased the availability of evidence for the
435 applicability of NPs enhanced remediation techniques – if these will be taken up broadly by the
436 market will however depend on the degree to which these information will be used by the
437 stakeholders and to which the stakeholders, in particular from academics, regulation and business,
438 continue and extend their dialogue.

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